mass spectral data and the NMR results described above. Furthermore, Bredereck[3] has reported that lactams react with phosphorus oxychloride and amines to give amidines via O-phosphorylated salts. It is not unreasonable to imagine a similar coupling reaction here.[4]

Experimental Section

Melting points were determined on a Thomas-Hoover capillary tube apparatus and are uncorrected. Infrared spectra were recorded on Perkin-Elmer Model 297 or 599B spectrophotometers. Hydrogen and carbon-13 NMR spectra were obtained on a $CDCl_3$ solution of **3** with a Varian XL-200 NMR spectrometer. Proton spectra were obtained in a few scans, using 12K data points with a sweep width of 2000 Hz and an acquisition time of 3 s and a pulse width corresponding to a flip angle of 30°. Carbon spectra were obtained in a few thousand scans with a sweep width of 10000 Hz, an acquisition time of 0.8 s, and a pulse width corresponding to a flip angle of 35°. Mass spectra were run on a Finnigan 4023 GC/MS. Microanalyses were performed by Atlantic Microlab.

Reaction of Pyrrolidone with Phosphorus Pentachloride. Phosphorus pentachloride (30 g, 0.14 mol) was added over a 10-min period to a stirred solution of 10 g (0.12 mol) of pyrrolidone in 50 mL of dry benzene at room temperature. The reaction mixture was then refluxed for 8 h, cooled, and poured into 100 mL of ice water. Basification of the aqueous layer with 50% sodium hydroxide gave a white solid, which was recrystallized from acetone/water to give 7.5 g (62%) of compound **3**: mp 51–52 °C; IR (KBr) 2960, 2920, 2860, 1620, 1600, 1430 cm^{-1}; mass spectrum, *m/e* (relative abundance) 206 (P + 2, 11), 204 (P, 18), 169 (35), 133 (15), 101 (10), 87 (10), 73 (10), 68 (22), 51 (28), 41 (100).

Anal. Calcd for $C_8H_{10}N_2Cl_2$: C, 46.85; H, 4.91; N, 13.66; Cl, 34.57. Found: C, 46.80; H, 4.95; N, 13.63; Cl, 34.53.

Registry No. 3, 33992-19-7; pyrrolidone, 616-45-5; phosphorus pentachloride, 10026-13-8.

(3) Bredereck, H.; Bredereck, K. *Chem. Ber.* **1961**, *94*, 2278.
(4) In the absence of additional information, we are hesitant to speculate further on a possible mechanistic pathway.

Acid-Catalyzed Rearrangements of Acetamido-Annelated Cyclobutenes. Formation and Properties of a 1,5-Dihydro-2*H*-azepin-2-one

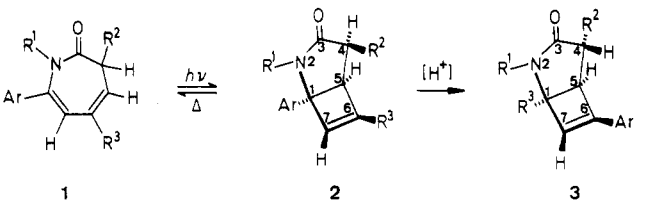
Hans-Dieter Becker* and Kenneth Gustafsson

Department of Organic Chemistry, Chalmers University of Technology and University of Gothenburg, S-412 96 Gothenburg, Sweden

Received March 27, 1981

Seven-membered cyclic dienamides (1,3-dihydro-2*H*-azepin-2-ones) **1**, in general, are unreactive in their electronic ground state but are prone to undergo photochemical isomerizations.[1] For example, irradiation of 7-aryl-substituted azepinones **1** in aprotic solvents smoothly gives acetamido-annelated cyclobutenes (azabicyclo[3.2.0]heptenones) **2** by intramolecular [2 + 2] cycloaddition.[2] In previous studies, acetamido-annelated cyclobutenes **2** have been shown to be thermally labile, regenerating azepinones **1** at elevated temperature (>200 °C).[3]

In an attempt to facilitate the thermally induced cycloreversion by acid catalysis,[4] we have now found that

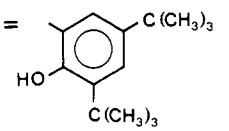


1 **2** **3**

1–3 a: $R^1 = CH_3$
b: $R^1 = n\text{-}C_3H_7$
c: $R^1 = c\text{-}C_6H_{11}$

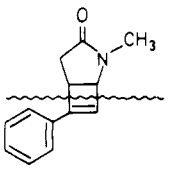
$R^2 = R^3 = C(CH_3)_3$

Ar =



acetamido-annelated cyclobutenes **2** can undergo novel transformations which complement the previously known cationic conversions of cyclobutenes, resulting in either ring contraction or ring enlargement and concomitant incorporation of a nucleophile.[5] Thus, refluxing solutions of **2a–c** in benzene in the presence of trifluoroacetic acid (TFA) smoothly gives the isomeric acetamido-annelated cyclobutenes **3a–c**. Isomers **3** differ structurally from starting compounds **2** by substituent interchange at C-1/C-6 and by epimerization at C-4.

As exemplified for the rearrangement product obtained from **2a**, the assignment of strucure **3** is based on the following spectroscopic evidence. In their infrared spectra, both **2a** and **3a** exhibit their carbonyl absorption at similar wavenumber (1665 and 1660 cm^{-1}, respectively), suggesting the rearrangement product to have retained the γ-lactam function. The ultraviolet spectrum of **2a** in ethanol shows the longest wavelength absorption maximum at 284 nm (ε 1900), while that of the rearrangment product **3a**, in agreement with extended conjugation, appears at 306 nm (ε 4100). Similar UV data [λ_{max} 291 nm (ε 4400)] have been reported for the structurally related azabicycloheptenone **4**.[6] Also analogous to **4**, the dominant mass spectral fragmentation of **3a** involves elimination of the arylacetylene moiety (M – 230).



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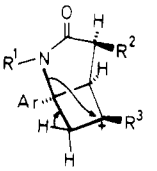


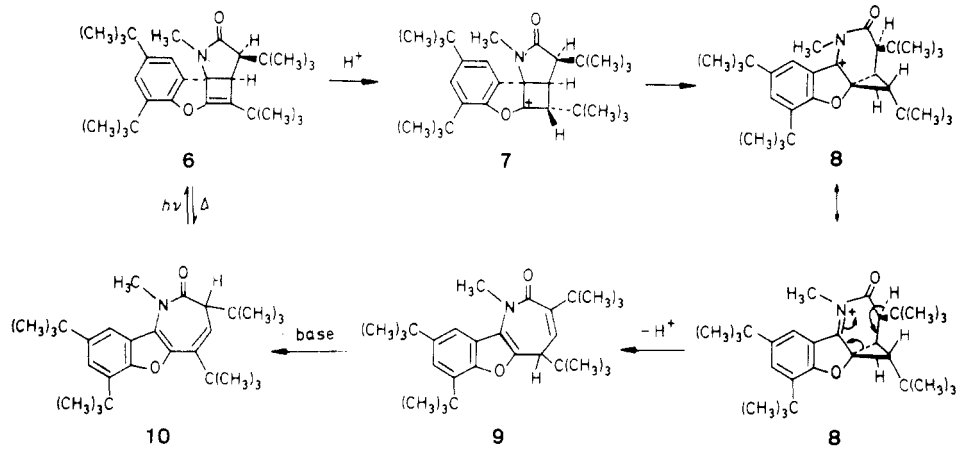
5

The ^1H NMR spectrum of **3a**, by and large, resembles that of **2a**, however, differences in coupling constants indicate the changes in dihedral angles between the protons at C-4, C-5, and C-7 which, as Dreiding molecular models suggest, may be brought about by the change of stereochemistry at C-4 (see Figure 1). Thus, in the ^1H NMR spectrum of the starting material **2a** (whose C-4 *tert*-butyl substituent has been confirmed to be endo oriented),[7] the

(1) Paquette, L. A. In "Nonbenzenoid Aromatics"; Snyder, J. P., Ed.; Academic Press: New York, 1969; Vol. 1, 249–310.
(2) Becker, H.-D.; Gustafsson, K. *J. Org. Chem.* **1977**, *42*, 2966. Becker, H.-D.; Turner, A. B. *Tetrahedron Lett.* **1979**, 4871.
(3) Chapman, O. L.; Hoganson, E. D. *J. Am. Chem. Soc.* **1964**, *86*, 498. Vogel, E.; Erb, G.; Lenz, G.; Bothner-By, A. A. *Justus Liebigs* Ann. Chem. **1965**, *682*, 1.
(4) Numerous examples of acid-catalyzed reversions of photochemical cycloadditions have been reported in the literature: Hirao, K.; Taniguchi, M.; Yonemitsu, O.; Flippen, J. L.; Witkop, B. *J. Am. Chem. Soc.* **1979**, *101*, 408. Becker, H.-D. *Justus Liebigs Ann. Chem.* **1973**, 1675. Greene, F. D. *Bull. Soc. Chim. Fr.* **1960**, 1356.
(5) Seebach, D. In "Methoden der Organischen Chemie (Houben-Weyl-Müller)", 4th ed.; Georg Thieme Verlag: Stuttgart, 1971; Vol. IV/4, p 422. Cf. also: Paquette, L. A.; Krow, G. R. *Tetrahedron Lett.* **1968**, 2139.
(6) Atherton, F. R.; Lambert, R. W. *J. Chem. Soc., Perkin Trans. 1* **1973**, 1079.
(7) Becker, H.-D.; Gustafsson, K.; Raston, C. L.; White, A. H. *Aust. J. Chem.* **1979**, *32*, 1931.

0022-3263/81/1946-4077$01.25/0 © 1981 American Chemical Society

Scheme I



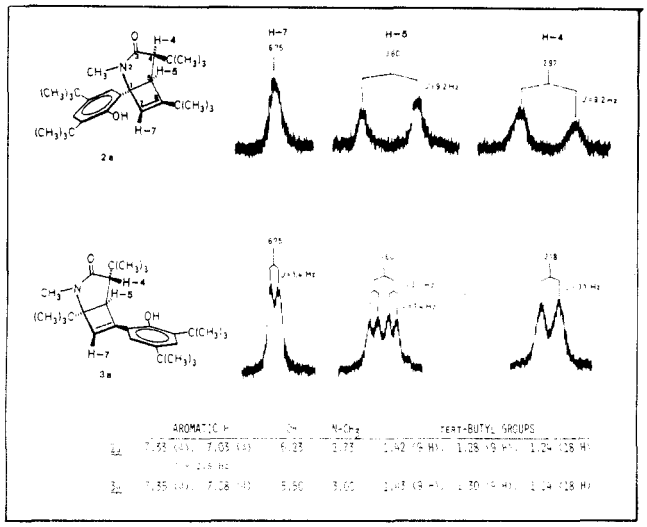


Figure 1. ^{1}H NMR spectral data of **2a** and its rearrangement product **3a**.

H-4 proton gives rise to a doublet (J = 9.2 Hz) at δ 2.97. As for the corresponding H-4 proton in the NMR spectrum of the rearranged product **3a**, its upfield shift (δ 2.18, J = 3.1 Hz), is attributable to shielding by the aryl moiety at C-6, thereby indicating the exo orientation of the C-4 *tert*-butyl substituent.

A mechanism which accounts for all the structural changes associated with the formation of **3a** involves protonation of the cyclobutene double bond in **2a** to give the cationic intermediate **5** which rearranges by way of 1,3-amido migration. Conceivably, the course of rearrangement is governed by both the nature of the migrating moiety and the bridgehead substituent Ar.

When the investigation was extended to the benzofuro-substituted azabicyclo[3.2.0]heptenone **6**, its TFA-catalyzed isomerization in boiling benzene was found to give the ring-enlarged product **9** (Scheme I). The structure of **9** is unique insofar as it contains the heretofore unknown 1,5-dihydro-2*H*-azepin-2-one ring system. Smooth conversion of **9** into the thermodynamically favored 1,3-dihydro-2*H*-azepin-2-one isomer **10** was accomplished by base catalysis. Thus, at least in principle, the catalytic reversibility of the photochemical intramolecular cycloaddition of azepinones has been demonstrated.

Interestingly, analysis of the new 1,5-dihydro-2*H*-azepin-2-one ring system by ^{1}H NMR spectroscopy reveals that two conformational isomers of **9** are present in a 3.5:1 ratio in chloroform solution at (or below) room temperature. The existence of two conformers of **9** is explicable

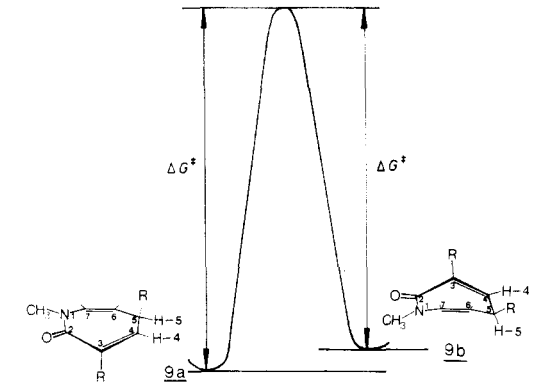


Figure 2. Energy profile for the interconversion of **9a** and **9b**.

in terms of a relatively high barrier of activation for the amide group folding motion and its consequential conformational changes. In the thermodynamically favored conformer **9a**, the observed coupling constant of 10 Hz corresponds to a calculated[8] dihedral angle between H-4 and H-5 of 19° and implies that the C-5 *tert*-butyl substituent is oriented axially (see Figure 2). As a result of the folding of the amide group, the C-5 *tert*-butyl substituent in conformer **9b** assumes the sterically less favorable quasi-equatorial orientation, concomitantly increasing the dihedral angle between H-4 and H-5 to 44°, as calculated[8] from the observed coupling constant of 6.5 Hz. From the chemical shift difference of 32 Hz between the *N*-methyl resonances in conformers **9a** and **9b** and from the coalescence temperature of 47 °C, a free energy of activation ($\Delta G^{\ddagger}$) of 17 kcal/mol was calculated[9] for the conversion of **9a** into **9b**. The conversion of **9b** into **9a** was found to be associated with an activation barrier of 16 kcal/mol (see Figure 2). At the temperature of coalescence, the ^{1}H NMR signal of the C-5 *tert*-butyl group has broadened (half-line-width of about 12 Hz), and it remains broadened even at 70 °C. A second, simultaneously occurring dynamic process may involve the twisting of the C(3)=C(4) double bond, as we deduce from the transient broadening around 45 °C of the C-3 *tert*-butyl signal.

The comparison of the dynamic properties of the 1,5-dihydro-2*H*-azepin-2-one **9** with those of the previously known 2,3-dihydro-2*H*-azepin-2-one **10** shows that the activation barrier for the amide group folding process in **10** is considerably lower. Even at −30 °C, the folding motion of the amide group in **10** is fast on the NMR time

(8) Bothner-By, A. A. *Adv. Magn. Reson.* **1965**, *1*, 195.
(9) Shanan-Atidi, H.; Bar-Eli, K. H. *J. Phys. Chem.* **1970**, *74*, 961.

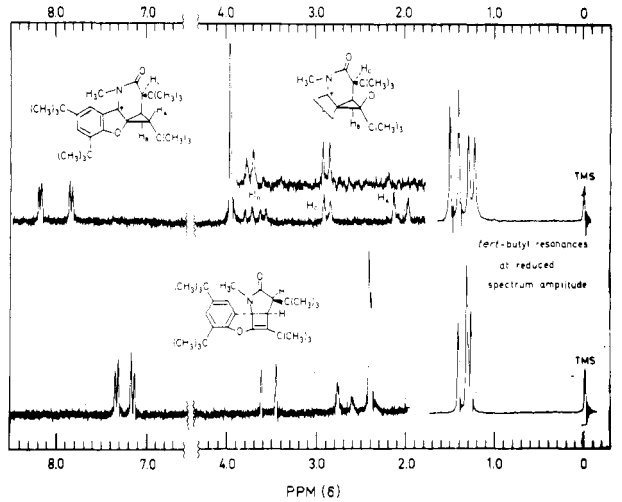


Figure 3. ^1H NMR spectra of **6** and its protonation product **8**.

scale, all ^1H NMR signals being sharp at this temperature. First at −60 °C, the signal due to the C-3 *tert*-butyl group broadens significantly. The observed half-line-width of 17 Hz at this temperature suggests that the activation barrier for the folding of the amide group in **10** may be about of 9 kcal/mol, as had previously[10] also been found for unsubstituted 2,3-dihydro-2*H*-azepin-2-one.

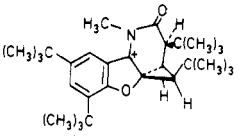
As for the mechanism of the acid-catalyzed rearrangement, the formation of **9** from **6** may be rationalized by the sequence of reactions outlined in Scheme I. This mechanism involves the protonation of the cyclobutene double bond so as to give, for reasons of resonance stabilization, cation **7** which undergoes ring contraction. Significantly, the resulting cation **8** is stable at room temperature and can be analyzed by spectroscopic means. In solution, it is characterized by its yellow color (λ_{max} 320 and 406 nm with ϵ 30 500 and 6600, respectively, in chloroform) and by its bright green fluorescence (λ_{max}^{em} 500 nm).

By use of deuterated TFA, the site of protonation of **6** was established by ^1H NMR (see Figure 3). The ^1H NMR spectrum of the ring-contracted cation **8** furthermore suggests that the protonation of the cyclobutene double bond in **6** occurs stereoselectively, as is indicated by the presence of only one stereoisomer which we assume to be the trans-substituted cyclopropane **8**. Inspection of Dreiding molecular models leads to the conclusion that the formation of the corresponding cis isomer **11** is highly improbable since steric overcrowding caused by the *tert*-butyl substituent should be immense.

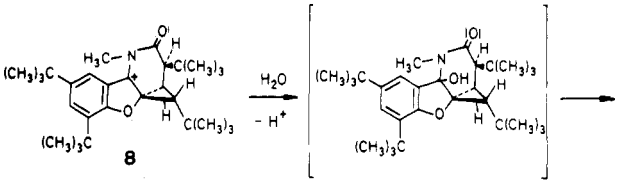
That we indeed are dealing with the ring-contracted cation **8**, rather than with the primary protonation product **7**, was established when the addition of water to the cationic species at room temperature was found to give the spiro-substituted cyclopropane **12**. Again, the ^1H NMR spectrum of **12** indicates the presence of a single stereoisomer which, in line with the arguments presented above, we assume to be the trans-substituted one.

Experimental Section

Melting points (uncorrected) were determined on a hot-stage microscope. Infrared spectra, in KBr disks, and electronic absorption spectra were taken on Beckman IR9 and Beckman DK2 instruments, respectively. The emission spectrum was obtained on an Aminco SPF 500 (corrected spectra) spectrofluorometer. NMR spectra were recorded on Bruker WH270 or Varian A60



11



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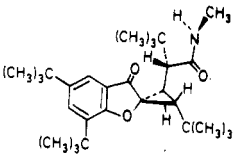


12

instruments, with chloroform-*d* as solvent and Me_4Si as an internal standard. Chemical shift data are reported in parts per million (δ). The ^{13}C NMR spectrum of **12** (in chloroform-*d*; chemical shifts relative to internal Me_4Si) was recorded at 67.88 MHz. Elemental analyses were performed by NOVO Microanalytical Laboratory.

1,3-Di-*tert*-butyl-6-(3,5-di-*tert*-butyl-2-hydroxyphenyl)-2-methyl-2-azabicyclo[3.2.0]hept-6-en-3-one (3a). A solution of **2a**[2] (2.2 g, 5 mmol) in benzene (75 mL) containing trifluoroacetic acid (TFA, 2 mL) was refluxed for 90 min. Vacuum evaporation of solvent gave an oily residue which crystallized upon addition of nitromethane. Recrystallization from nitromethane gave 1.7 g (77%) of colorless crystals: mp 223–224 °C; IR 3340 (br, m), 1660 (s), 1620 cm^{-1} (m); UV (ethanol) λ 217 nm ($10^{-3}\epsilon$ 29.0), 260 (15.3), 268 (sh, 12.5), 306 (4.1).

Anal. Calcd for $C_{29}H_{45}NO_2$ (mol wt 439.68): C, 79.22; H, 10.32. Found: C, 78.98; H, 10.25.

1,3-Di-*tert*-butyl-6-(3,5-di-*tert*-butyl-2-hydroxyphenyl)-2-*n*-propyl-2-azabicyclo[3.2.0]hept-6-en-3-one (3b). The rearrangement of **2b**[2] carried out as described for **2a**. Recrystallization from ethanol gave colorless crystals: 57%; mp 231–233 °C; IR 3330 (br, s), 1665 (s), 1620 cm^{-1} (m); UV (ethanol) λ 216 nm ($10^{-3}\epsilon$ 30.9), 260 (16.0), 268 (sh, 13.3), 306 (4.2). ^1H NMR δ 7.36 (d, J = 2.5 Hz, 1 H), 7.08 (d, J = 2.5 Hz, 1 H), 6.67 (d, J = 1.2 Hz, 1 H), 5.53 (s, OH), 3.91–3.08 (m, 3 H), 2.22 (d, J = 3.4 Hz, 1 H), 1.93–0.75 (m, containing sharp peaks at 1.43, 1.30, and 1.15, 41 H).

Anal. Calcd for $C_{31}H_{49}NO_2$ (mol wt 467.74): C, 79.60; H, 10.56. Found: C, 79.60; H, 10.53.

1,3-Di-*tert*-butyl-6-(3,5-di-*tert*-butyl-2-hydroxyphenyl)-2-cyclohexyl-2-azabicyclo[3.2.0]hept-6-en-3-one (3c). The rearrangement of **2c**[2] was carried out as described for **2a**. The crude reaction product was recrystallized by adding nitromethane to a solution in ether: yield 87%; colorless crystals; mp 137–139 °C; IR 3500 (m), 1695 (s), 1620 cm^{-1} (m); UV (ethanol) λ 219 nm ($10^{-3}\epsilon$ 28.2), 260 (17.3), 268 (sh, 13.5), 307 (4.0); NMR δ 7.35 (d, J = 2.5 Hz, 1 H), 7.10 (d, J = 2.5 Hz, 1 H), 6.42 (d, J = 2.2 Hz, 1 H), 5.37 (s, OH), 3.64 (m, 2 H), 2.57 (d, J = 2.2 Hz, 1 H), 1.90–1.10 (m, sharp peaks at 1.43, 1.29, 1.14, and 1.10, 46 H).

Anal. Calcd for $C_{34}H_{53}NO_2$ (mol wt 507.80): C, 80.42; H, 10.52. Found: C, 80.30; H, 10.34.

3,5,6,8-Tetra-*tert*-butyl-1-methyl-1,5-dihydro-2*H*-benzofuro[2,3-*f*]azepin-2-one (9). A solution of **6**[2] (2.2 g, 5 mmol) in benzene (75 mL) containing TFA (2 mL) was refluxed for 90 min. During this time, the originally green-fluorescent solution turned pale yellow. Vacuum evaporation of solvent gave an oily residue which crystallized upon treatment with nitromethane. Recrystallization from ethanol gave 1.75 g (79%) of colorless crystals: mp 162–164 °C; IR 1655 (s), 1615 cm^{-1} (s); UV (ethanol) λ 215 nm (sh, $10^{-3}\epsilon$ 30.6), 269 (11.5), 278 (sh, 10.5), 290 (7.7); NMR (of **9a** at 12 °C) δ 7.39 (d, J = 2 Hz, aromatic H), 7.26 (d, J = 2 Hz, aromatic H), 6.31 (d, J = 10 Hz, H-4), 3.47 (s, NCH_3), 3.41

(10) Mannschreck, A.; Rissmann, G.; Vögtle, F.; Wild, D. *Chem. Ber.* **1967**, *100*, 335.

(d, J = 10 Hz, H-5), 1.50, 1.39 (two *tert*-butyl groups), 1.24 (C-3 *tert*-butyl group), 0.97 (C-5 *tert*-butyl group); NMR (of **9b**) δ 7.36, 7.26 (aromatic H), 6.19 (d, J = 6.5 Hz, H-4), 3.59 (s, NCH_3), 3.32 (d, J = 6.5 Hz, H-5), 1.52, 1.39 (two *tert*-butyl groups), 1.25 (C-3 *tert*-butyl group), 1.17 (C-5 *tert*-butyl group).

Anal. Calcd for $C_{29}H_{43}NO_2$ (mol wt 437.67): C, 79.58; H, 9.90. Found C, 79.53; H, 9.93.

Base-Catalyzed Isomerization of 9 (10). Potassium *tert*-butoxide (60 mg) was added to a solution of **9** (219 mg, 0.5 mmol) in dimethyl sulfoxide (30 mL) and ethanol (3 mL) at 80 °C under nitrogen blanketing. The reaction mixture was kept at 80–85 °C under nitrogen for 80 min. Addition of water (15 mL) gave a colorless crystalline precipitate which was removed by filtration and recrystallized from aqueous ethanol: yield 180 mg (82%); mp 181–182 °C (lit.[2] mp 182–183 °C), no depression upon admixture of authentic[2] **10**.

Acid-Catalyzed Rearrangement of 6 in the Presence of Water (12). Trifluoroacetic acid (2 mL) was added to a solution of **6** (1.4 g, 3.2 mmol) in ethanol-free chloroform (5 mL) at room temperature. After 15 min, the green–fluorescent solution was diluted with a mixture of methanol (15 mL) and water (5 mL). After 45 min of stirring, the solution had turned colorless. Vacuum evaporation of solvents gave an oily residue which crystallized upon treatment with methanol. Recrystallization from aqueous methanol gave 1.1 g (73%) of colorless crystals: mp 195–196 °C; IR 3340 (s), 1680 cm^{-1} (s); UV (in ethanol) λ 218 nm ($10^{-3}\epsilon$ 29.5), 223 (29.0), 258 (16.6), 265 (sh, 13.0), 336 (5.1), 345 (sh, 4.7); NMR δ 7.65 (d, J = 2 Hz, 1 H), 7.55 (d, J = 2 Hz, 1 H), 5.96 (br m, NH), 2.81 (d, J = 4.5 Hz, NCH_3), 2.54 (t, J = 9.5 Hz, 1 H), 2.46 (d, J = 9.5 Hz, 1 H), 1.62 (d, J = 9.5 Hz, 1 H), 1.44 (s, 9 H), 1.33 (s, 9 H), 1.04 (s, 9 H), 0.86 (s, 9 H); ^{13}C NMR 199.7 (C=O), 173.6 ppm (NC=O).

Anal. Calcd for $C_{29}H_{45}NO_3$ (mol wt 455.68): C, 76.44; H, 9.95. Found: C, 76.28; H, 9.87.

Acknowledgment. We are gratefully indebted to Mr. Gunnar Svensson for technical assistance and to Mr. Reine Torberntsson and Mr. Kjell Andersson for their help with the NMR experiments.

Registry No. 2a, 60434-60-8; **2b**, 60434-61-9; **2c**, 60434-62-0; **3a**, 78591-95-4; **3b**, 78591-96-5; **3c**, 78591-97-6; **6**, 60434-70-0; **8**, 78624-41-6; **9**, 78591-98-7; **10**, 60434-67-5; **12**, 78591-99-8.

Lewis Acid Catalyzed Methanolysis of a Phosphate Triester

William S. Wadsworth, Jr.

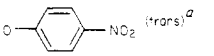
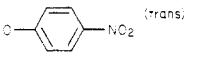
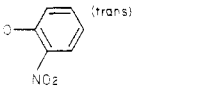
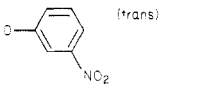
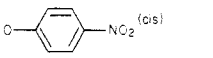
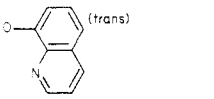
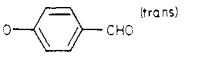
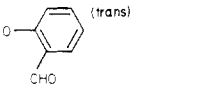
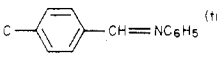
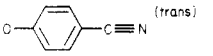
Department of Chemistry, South Dakota State University, Brookings, South Dakota 57007

Received March 17, 1981

Trialkyl phosphates are both found in nature and used as commercial products. Because of their utility, it is of interest to determine those factors which influence their reactivity. In a recent publication,[1] we described the proton-catalyzed methanolysis of 2-substituted 5-(chloromethyl)-5-methyl-2-oxo-1,3,2-dioxaphosphorinan (1). We found that at low acid concentrations the configuration at phosphorus was retained while at elevated proton concentrations both retention and inversion occur, with inversion predominating. At low acid concentrations protonation takes place on phosphoryl oxygen, the most basic site. Displacement occurs via a pentavalent intermediate. At high concentrations additional protonation of the leaving group leads to both retention and inversion with

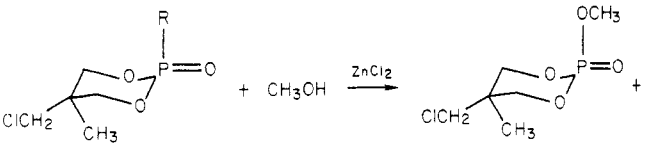
(1) Gehrke, S. H.; Wadsworth, W. S., Jr. *J. Org. Chem.* **1980**, *45*, 3921.

Table I. Methanolysis Catalyzed by Zinc Chloride

R	time for half-reaction, h[a,b]	% trans	% cis
	4[a]	40	60
	21[d]	45	55
	∞	NR[e] after 15 days	
		40	60
	insol in CH_3OH at room temp[c]	65	35
	>245 (42%)	100	0
	∞	NR	
	∞	NR	
	12	27	73
	3.6	46	54

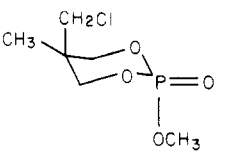
[a] Solutions 0.1 M in ester and 0.1 M $ZnCl_2$. [b] Reactions run at room temperature. [c] Reactions run at reflux. [d] 0.05 M $ZnCl_2$. [e] NR, no reaction.

We are limited by the lack of solubility of most metal salts in methanol. Our work, therefore, was restricted to zinc chloride which in methanol is undoubtedly ionized and the cation solvated.[2] The system is relevant, for zinc ion is a common requirement for a number of enzymatic systems.[3]



1 (trans)

trans



cis

Methanolysis occurs readily in those cases where the leaving group is capable of complex formation with zinc ion (Table I). The product ratio, 60% inversion, is not unlike that found in proton catalysis at high acid concentrations. The ratio does not change appreciably at catalyst concentrations greater than 1 equiv but does tend to decrease at lower concentrations. A greater than equivalent amount of catalyst increases the initial rate of methanolysis only slightly. The reactions are not first

(2) Cotton, F. A., Wilkinson, G. "Advanced Inorganic Chemistry", 4th ed.; Wiley: New York, 1980; p 599.

(3) Ochiai, Ei-Ichiro "Bioinorganic Chemistry"; Allyn and Bacon: Boston, MA, Chapter 13.

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